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LOW COST, HIGH EFFICIENCY REGENERATOR FOR CRYOCOOLERS

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March 1994

Final Report

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This report has been reviewed and is approved for publication.

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13. Supplementary Notes

14. Abstract A new regenerator for cryocoolers has been invented. Phase I has demonstrated that the regenerator can be fabricated as conceived. The new regenerator should improve performance of the "Brilliant Eyes" cryocoolers by more than 20 percent without modifications. New cryocoolers designed from scratch to utilize the new technology have the potential to double current cryocooler performance, dramatically improving the ratio of heat transfer to pressure drop, through regenerator. This results in improved net refrigeration and coefficient of performance, which are particularly important for space applications, where payload and power consumption are critical. Higher COP means that a smaller cryocooler can do the same job as a larger one. Higher COP is also important in tactical cryocooler applications where batteries are the power source: the batteries last longer. The regenerator can be fabricated from a variety of materials, including materials with high heat capacity at temperatures approaching absolute zero.

15. Subject Terms regenerator, Cryocoolers, Brilliant Eyes, COP, Batteries

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<u>Yaron Consulting:</u>

Principle Investigator: R. Yaron

Design and analysis: M. Mitchell, D. Fabris, S. Shokralla

In addition, special thanks are also due Dr. R. Radebaugh of the National Institute of Science and Technology for his many useful technical comments and suggestions, to Mr. G. Kramer of Hughes Aircraft, and to F. Martinez and Capt. P. Thomas of AFSTC for their overall support of this project.

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SECTION 1.0

THE TECHNICAL PROBLEM AND ITS SOLUTION

"The regenerator is often one of the major loss sources in regenerative-cycle refrigerators. It contributes loss terms due to its limited heat transfer units, limited matrix specific heat, pressure drop, dead volume, and axial thermal conduction. An optimum design of these regenerators would significantly improve the performance of the overall refrigerator." (Radebaugh and Louie, [Ref. 1])

A new rolled foil regenerator ("RFR") has been invented. The conclusions of Phase I are that the regenerator can be fabricated as conceived. The RFR has the potential to improve the overall coefficient of performance ("COP") of the Air Force 65 K SSC (Standard Spacecraft Cryocooler) by more than 20 percent at 60 K and more than 50 percent at 45 K. For cryocoolers designed to take full advantage of the characteristics of the RFR, the improvement should be significantly larger.

The new regenerator simultaneously reduces pressure drop losses and improves heat transfer, thereby reducing losses from irreversibilities. It can also increase heat capacity of the matrix by increasing its mass without altering its flow characteristics, reducing temperature swing losses. It minimizes axial thermal conduction losses. Since a large part of the refrigeration is dissipated in these losses, even a small reduction in the losses produces a large improvement in the net refrigeration available for use. Maximum improvement in performance will be obtained when cryocoolers are designed from scratch to take full advantage of the improved characteristics of the RFR.

The primary objective of Phase I was to develop a detailed conceptual design, select a preferred pattern, and prepare a prototype development plan, schedule and cost estimate for the balance of the program. The overall objective of Phase II will be to demonstrate RFR technology for regenerative cryocoolers and to deliver an RFR for the Air Force 65 K SSC.

1.1 PHASE I

The RFR has been made possible by combining three advanced theoretical and practical techniques; (1) advanced computational fluid dynamics ("CFD") modeling of the RFR concept; (2) analysis of RFR performance in the SSC; (3) state-of-the-art micro-machining required to create the RFR. To demonstrate these techniques in Phase I, the following tasks were performed:

a. Initial selection of foil pattern to be tested in the RFR.

b. Adaptation of microCOMPACT CFD code obtained from Innovative Research, Inc., to model the flow friction and heat transfer characteristics of the RFR.

c. Validation of the adaptation of the microCOMPACT CFD code against a well-known case.

d. Calculation of flow friction factors and convective heat transfer factors for the RFR.

e. Analysis of the SSC with reference to performance data for the Hughes SSC #2 spacecraft cooler.

f. Incorporation of an RFR option into two Stirling computer models.

g. Comparative analysis of the performance of the SSC with its original-equipment woven wire screen regenerator and with an RFR.

h. Micro-machining fabrication tests on foil, in a range of pattern dimensions, to confirm and improve the micro machining and insure the quality of the process and materials.

i. Preparation of a task plan, schedule and cost estimate for follow-on development of an engineering model.

1.2 ANALYSIS

A major objective of the Phase I effort was to analyze the predicted performance of the micromachined foil regenerator pattern seen in Fig. 1. The pattern was tested analytically using the microCOMPACT CFD code to determine the impact of the pattern upon pressure drop and heat transfer.

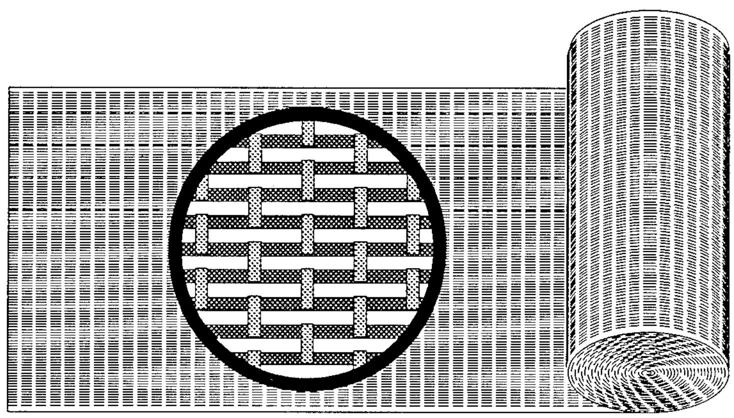

Figure 1. Micromachined foil regenerator.

The microCOMPACT CFD code was used to evaluate two-dimensional flow characteristics of the pattern at Reynolds numbers consistent with fluid flows in a cryocooler regenerator. COMPACT is a commercial software package developed originally for use on supercomputers by Professor Suhas V. Patankar's team from the University of Minnesota. Professor Patankar is a leader in computational heat transfer and fluid flow [Refs. 2 and 3]

The workstation version, called microCOMPACT, is offered commercially by Innovative Research, Inc., of Minneapolis. Its value has been recognized by researchers in a variety of fields. One testimonial, supplied by Dr. Ab Hashemi of Lockheed Missiles and Space Company, was confirmed in personal conversations with Dr. Hashemi.

Before it was used in Phase I, microCOMPACT was first used to solve the well-studied case of steady, fully developed laminar flow between two parallel plates. The code results were within 0.2 percent of the analytical solution for both friction factor and convective heat transfer coefficient.

With its validity established, microCOMPACT was used to develop friction and heat transfer coefficients for the RFR. Pressure drop and convective heat transfer for the RFR were obtained for various flow rates (i.e. Reynolds numbers). Those results were converted into friction and heat transfer coefficients [Ref. 4] as follows:

$$St \cdot Pr^{2/3} = 20/Re \tag{1}$$
$$f = 60 \cdot Re^{-0.92} \tag{2}$$
$$\alpha = (St \cdot Pr^{2/3}) / f \tag{3}$$

St	Stanton number (h/Gc_p), a heat transfer modulus
Pr	Prandtl number ($\dot{m}c_p/k$), a fluid properties modulus
Re	Reynolds number ($4r_hG/\mu$), a flow modulus
f	Mean friction factor
α	Regenerator effectiveness modulus
h	Unit conductance for thermal-convection heat transfer
G	Regenerator flow-stream mass velocity
c_p	Specific heat at constant pressure
μ	Viscosity coefficient
k	Unit thermal conductivity
r_h	Hydraulic radius

To achieve the best performance from a regenerator, it is necessary to maximize heat transfer while minimizing pressure drop caused by fluid friction. These goals are inconsistent. Heat transfer may be improved by increasing the specific area of the regenerator matrix and reducing the hydraulic radius of the flow passages. That, however, tends to increase the pressure drop. Regenerator performance can be improved by optimizing the ratio of heat transfer to pressure drop loss.

Typical Reynolds numbers in a cryocooler regenerator range from 0 to < 100. At the relevant Reynolds numbers, heat transfer is determined largely by fluid velocity. In this respect, screens and the RFR are quite different. Because large portions of the wires in screens are in near contact with, or in the "wind shadow" of other wires, only a relatively small area of the screens is exposed to the full-velocity flow of the fluid. In the RFR, however, the fluid flow is quite uniform throughout, and much of the surface area is therefore exposed to the full-velocity flow.

The result is a much higher heat transfer coefficient for the RFR, especially at Reynolds numbers below 40. This relationship is illustrated in Figure 2.

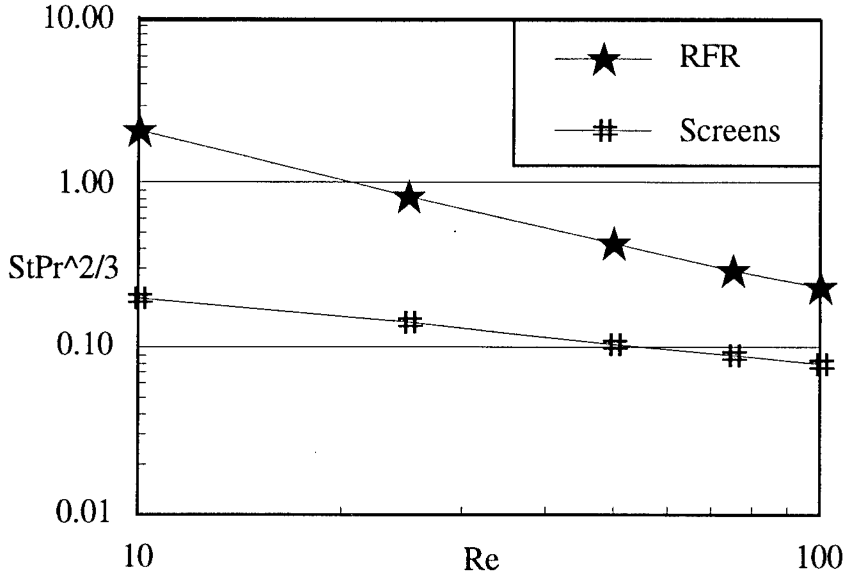

Figure 2. Heat transfer coefficients as function of Reynolds number.

Pressure drop losses are a major source of regenerator ineffectiveness in cryocoolers. These losses were analyzed with microCOMPACT. At Reynolds numbers below about 40, flow friction is largely a function of surface area. Friction factor for an RFR is quite similar to the friction factor for stacked screens, as illustrated in Fig. 3.

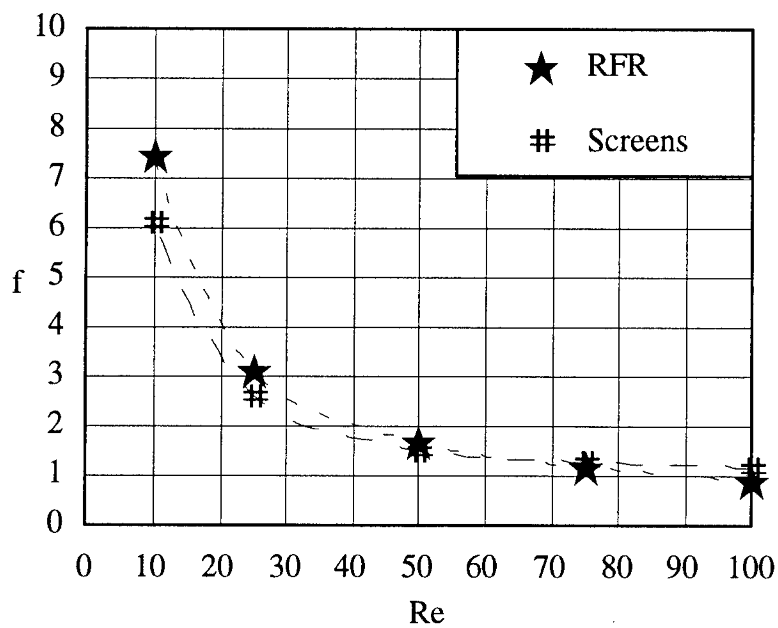

Figure 3. Flow friction coefficient for RFR and stacked screens.

The regenerator effectiveness modulus a for the RFR and comparable stacked screen case are shown in Figure 4. In that range, the effectiveness ratio for the RFR remains above 0.25, decreasing slightly as the Reynolds number increases. A comparable 400-mesh stacked screen regenerator, by contrast, has an effectiveness ratio of less than 0.07 at best and < 0.05 at Reynolds numbers below 20.

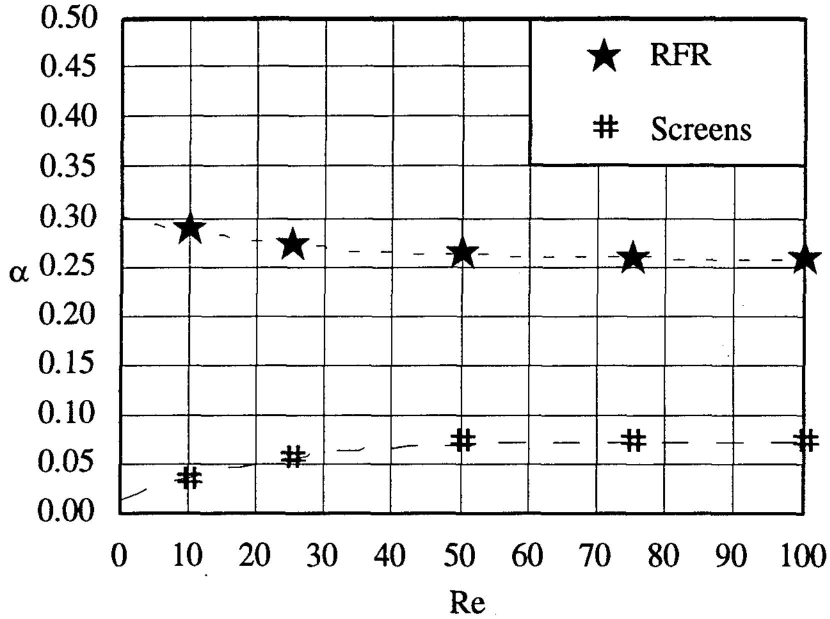

Figure 4. Ratio of heat transfer coefficient to friction factor.

The effectiveness ratio of the RFR is always more than 3 times the effectiveness ratio of the stacked screens and its superiority is larger in the lower Reynolds numbers where cryocooler regenerators usually operate.

The RFR is unique in its ability to combine very high heat transfer characteristics with low axial conductivity and uniform flow. Due to its high specific heat transfer, or number of heat transfer units ("NTU"), larger flow passages are possible, resulting in smaller pressure drop loss and better contamination resistance and thus greater reliability.

1.2 MODELLING AN RFR-EQUIPPED CRYOCOOLER

The heat transfer and the flow friction coefficients from equations 1 and 2 and the specific geometry (i.e. hydraulic radius and porosity) of the selected RFR were provided to the computer codes used to evaluate performance of the SSC #2. The results were compared to results obtained with the SSC #2's original-equipment stacked screen regenerator.

The two codes used are a second and a third-order codes. The second-order is a variation of the Urieli/Berchowitz [Ref. 5] code. It includes empirical friction and heat transfer data of actual cryocoolers. The code was developed by Urieli and the Principal Investigator. The other code is the third-order MS*2 Stirling Cycle Code [Refs. 6, and 7], a proprietary code developed by subcontractor Mitchell/Stirling Machines/Systems, Inc. These codes differ in their computational approach. The Urieli/Yaron code was specifically to model regenerative cryocoolers of all kinds; the MS*2 code is a general-purpose code designed to model engines, refrigerators and cryocoolers, but limited to Stirling-type regenerative machines. The specifics of the codes are described in the Appendix.

The Hughes Aircraft SSC #2 65 K standard spacecraft cryocooler was selected for the first demonstration of the RFR at the end of the development program of this contract. Dimensions, operating conditions and performance data were obtained from the manufacturer. Results of analysis with both codes were compared with test data for the SSC #2.

In order to estimate the relative performance of the cryocooler equipped with an RFR as compared to its performance with the original-equipment stacked screen regenerator, both codes were modified to incorporate the heat transfer and flow friction coefficients developed with the aid of the microCOMPACT CFD code and expressed in equations 1 and 2. The SSC #2 was then modelled with both codes for both regenerators. The results of the modelling showed that both codes predicted the performance of the SSC #2 with its original regenerator quite accurately. See the Appendix.

Both codes also predicted substantial improvement in performance with the RFR substituted for the original stacked screen regenerator. The comparison is plotted in Figures 5 and 6 for the Urieli/Yaron and MS*2 codes, respectively.

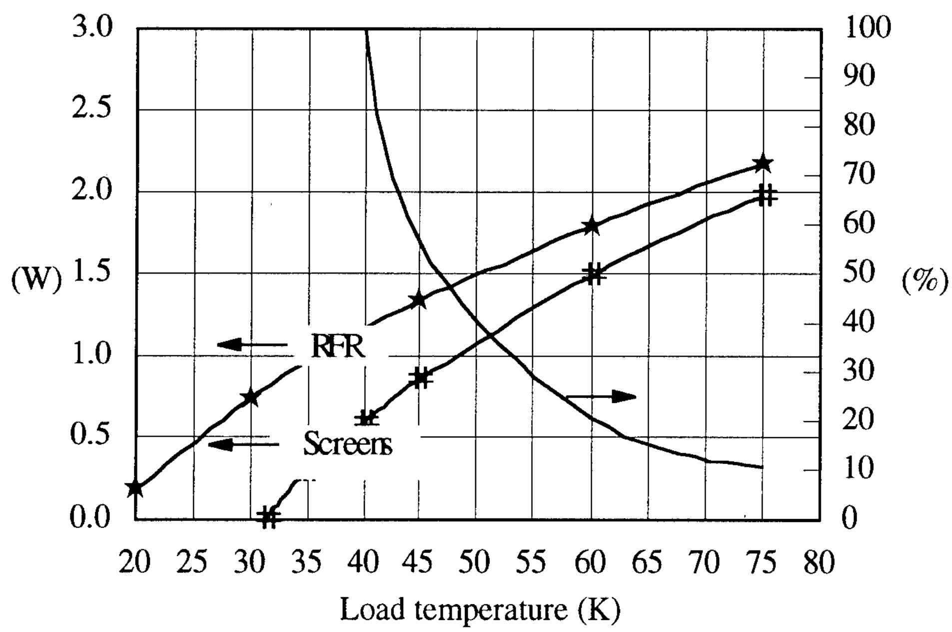

Figure 5. Improvement in cooling capacity with RFR according to Urieli/Yaron analysis.

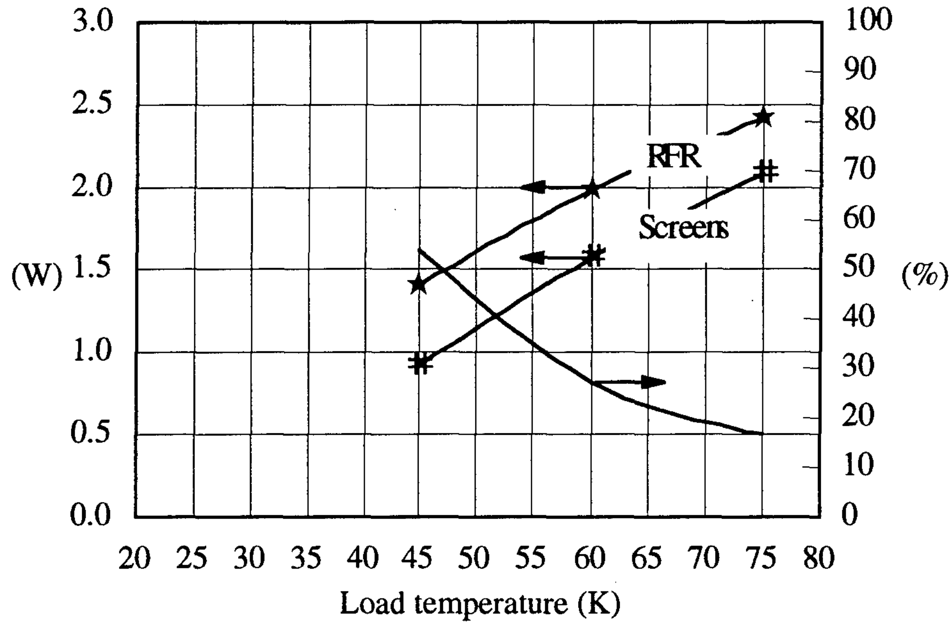

Figure 6. Improvement in cooling capacity with RFR according to the MS*2 code.

As may be seen by inspection of Figures 5 and 6, the improvement in cooling capacity from using the RFR is larger at lower temperatures. For example, at 60 K, the predicted performance improvement is somewhat more than 20 percent while at 45 K, the performance improvement is greater than 50 percent. The RFR-equipped single-stage spacecraft cryocooler is predicted to reach a no-load temperature below 20 K. It should be noted that all results reflected in Figures 5 and 6 are based upon fixed operating conditions (i.e. pressure, strokes, frequency and phase angle). At lower temperatures, further optimization of these parameters could be expected to produce further improvements in performance.

SECTION 2.0

FABRICATION OF THE FOIL PATTERN

The theoretical benefits of the RFR would be academic if it could not be made. The desired pattern can be micromachined in stainless steel, alloys of copper, lead and various other metals. Beryllium copper was chosen because it is a cryogenic material, with known properties and high reliability. It has desirable mechanical properties both for forming and in operation. It has good thermal properties in terms of both heat capacity and conduction. Phase I demonstrated that the desired pattern can be micromachined in a beryllium copper foil 50 μ thick. Three different slit patterns 75-μ, 100-μ and 125-μ in width were fabricated. All three met QA (quality assurance) criteria. The sample with 100-μ slits is shown in Figure 7.

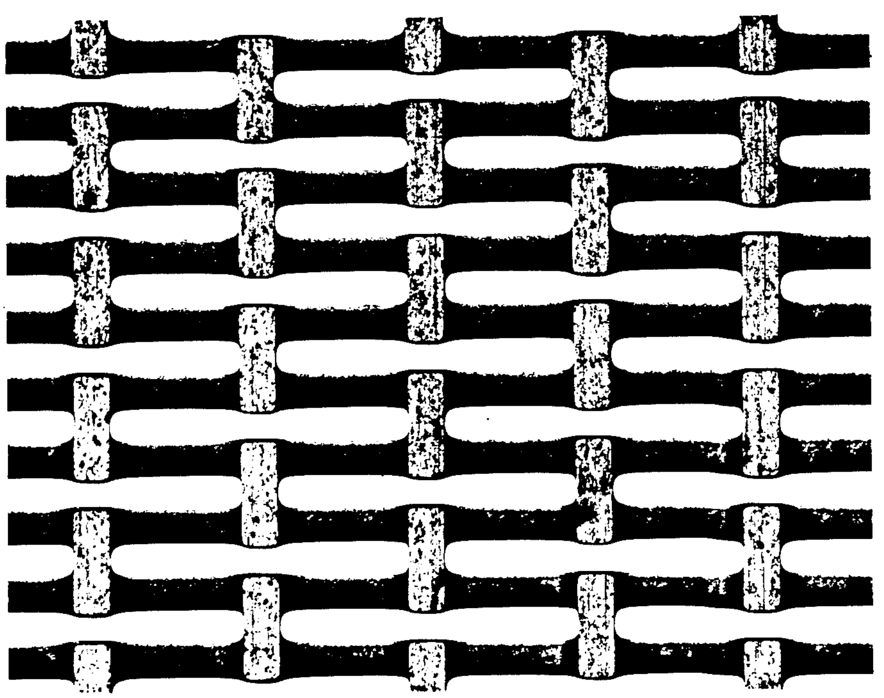

Figure 7. Micromachined 50-μ beryllium copper foil, 100-μ slits (X50).

SECTION 3.0

RECOMMENDED PHASE II DEVELOPMENT PLAN

3.1 PHASE II TECHNICAL OBJECTIVES

The overall technical objectives of Phase II are to fabricate, test and qualify a rolled foil regenerator ("RFR") that will improve performance of the "Brilliant Eyes" spacecraft cryocooler. The probability of success in fabrication and testing is high. Phase I demonstrated that the RFR should improve the performance of the Air Force 65 K SSC by more than 20 percent at 60 K. It also demonstrated that the key fabrication technology - micromachining of metal foil - works as expected.

The manufacture of a complete regenerator will require demonstration of techniques for rolling the foil, confining it in the rolled condition and inserting it into a cryocooler regenerator. These steps will require significant experimentation, but none are expected to create insurmountable difficulties.

The amount of performance improvement actually attainable remains to be determined. It will undoubtedly depend in part on the micromachined pattern selected. Thus, a specific objective of Phase II will be to identify the parameters that determine optimal foil thickness and micromachined pattern.

The commercial significance of the program is that improved regenerators will find a market in cryocoolers for industrial and medical applications as well as a variety of defense systems. Examples include cryopumps used in the manufacture of computer chips and cryogenic coolers used to cool radiation shields of magnetic resonance imaging (MRI) machines used for medical diagnosis. The total market for cryocoolers today exceeds 10,000 units per year. Development of new, "high temperature" (but still cryogenic) superconducting devices will vastly increase that market in the future.

3.2 PHASE II WORK PLAN

The overall objective of the work plan is to develop an RFR that works better than existing stacked screen regenerators in cryocoolers operating in the 65 K temperature range. The plan calls for three iterations of preliminary design and testing prior to installation and testing of the final version in the SSC #2 spacecraft cryocooler.

The three preliminary rounds of design and testing will be conducted in parallel in the contractor's facilities and at the NIST. Testing of varying regenerator patterns at various operating conditions will provide insight into the heat transfer and pressure drop characteristics of an optimum RFR.

The major task subdivisions are shown in Figure 8. Initially, the test-bed will be set up and debugged while the first RFR pattern is being designed and fabricated. Completion of the first round of tests will be followed by an interim report and a critical design review before the second round of tests begins. Similar procedure will be followed for the second and third iterations of the design. The final technical task will be to design, fabricate and supply an RFR for the SSC #2, which will be delivered to Hughes Aircraft for testing. Submission of the final report will then complete the project.

The time schedule for the major tasks of the project is shown in Figure 8. Figure 9 is an expanded version of Figure 8 showing in detail the tasks that make up each round of testing.

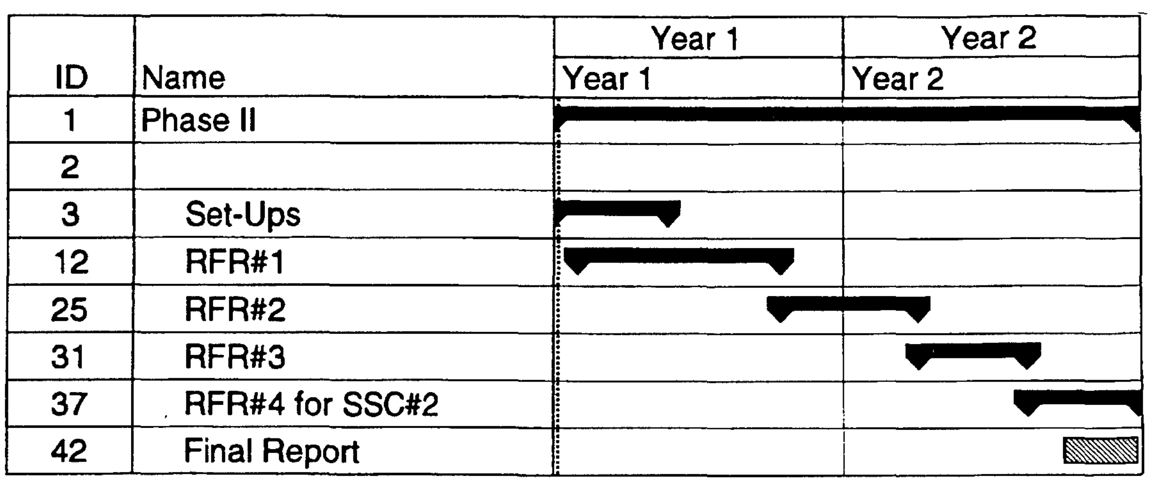

Figure 8. Major tasks of the project

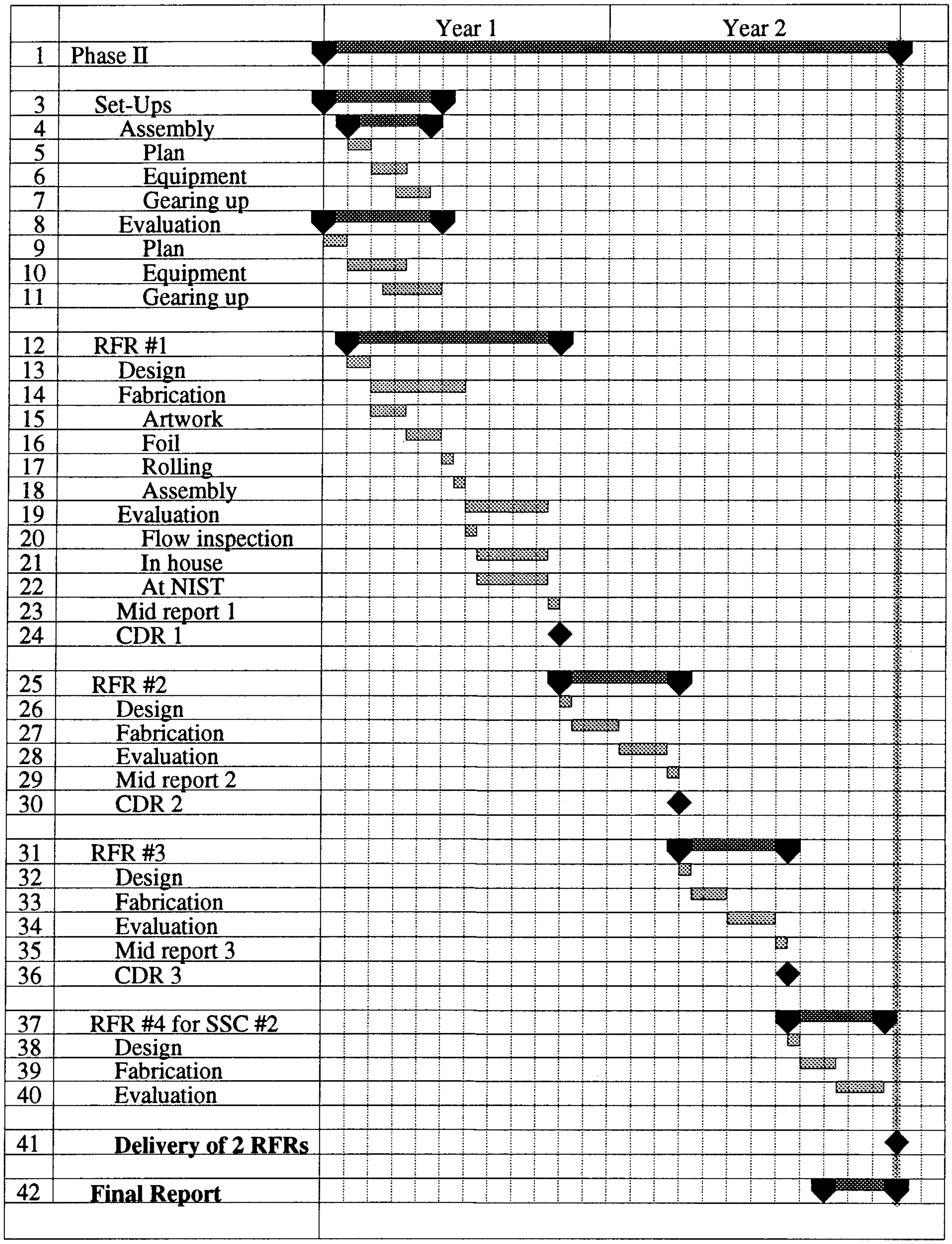

Figure 9. Expanded version of figure 8.

3.3 TASK BREAKDOWN

The left hand column of the charts, headed "ID", contains identification numbers for the separate tasks that make up the project.

ID #3: "Set-Up" includes the subtasks shown in ID #s 4-11.

ID #4: "Assembly" includes the subtasks required to set up the shop facilities required to build RFR and to dis-assemble, modify and re-assemble two 1 W "common module" tactical cryocoolers that will be used for in-house testing of RFR prototypes.

ID #5: "Plan" covers development of a series of procedures to be followed whenever a cryocooler is opened and closed in connection with installation of a new regenerator. In order for comparative test results to be valid, it is essential that the operating conditions of the test-bed cryocooler be maintained constant from one test series to another. Equipment required for the disassembly/re-assembly process will be identified as part of this task.

ID #6: "Equipment" covers acquisition and installation of the equipment required for the disassembly/re-assembly process. A critical part of this system will be the vacuum bakeout oven, needed to ensure that contaminant gases are removed before the testbed cryocooler is charged with helium. To ensure that the helium used to charge the cryocoolers is clean, special gas handling equipment will be required. Specialized tools may also be required to open and close the test-bed cryocooler.

ID #7: "Gearing Up" covers shakedown of the equipment acquired under ID #6: It includes trial runs with the assembly procedures and equipment to ensure that assembly and bakeout can be accomplished reliably and repeatably.

ID #8: "Evaluation" covers the testing process. The test program must be planned and the appropriate equipment acquired, installed and checked out. These tasks are covered in ID #s 9-11.

ID #9: "Plan" covers development of a detailed plan for the test rig and a plan for the experiments to be conducted with it. The test rig will be run first to establish baseline performance of two common module cryocoolers with their original equipment stacked screen regenerator in place. The coolers will be identical makes and models, so that they should deliver essentially identical performance. They will both be tested and calibrated against each other. One will be set aside as a "control" for the experiments to be run with the other, which will serve as test-bed for the RFR. Thereafter, the same test rig will be used to test successive iterations of the RFR design against the control. At the end of the testing program, the cryocooler that was used as the test-bed will be refitted with its original regenerator and retested against the control. Details of both the rig and the test program must be worked out in advance to ensure that the assembly and testing of the test rig and subsequent testing of regenerators will proceed smoothly and on time.

ID #10: "Equipment" covers purchase and installation of equipment specified in the plan developed in task ID #9. The equipment to be purchased and installed will include the test-bed cryocooler and its test bench. The test bench will include gas-handling equipment, equipment to power and control the cryocooler, and equipment to monitor power input, pressure and temperature. Available data acquisition equipment will be augmented as necessary. A particularly critical item will be a differential pressure transducer to be connected around the regenerator. That transducer will allow direct reading of pressure drop during the test program. Equipment to measure conduction in the regenerator will also be included.

The test-bed cryocooler will have a mechanically driven displacer as well as mechanically driven piston. The decision to use a mechanically driven displacer is based upon the likely difference in pressure drop between the original, stacked screen regenerator and the RFR. If the RFR were to be used in a split Stirling cryocooler without modification, the difference in pressure drop would produce a change in phase angle of the displacer relative to the piston, and direct comparison of performance would be far less meaningful. Hence the decision to select a 1-W common module tactical cryocooler as test-bed.

ID #11: "Gearing up" covers shakedown of the data acquisition arrangements to ensure that they will function reliably and repeatably over the whole course of planned testing procedures.

ID #12: "RFR#1" includes design, fabrication, testing and evaluation of the first RFR. Each of those main tasks is broken down into subtasks in ID #s 13-24.

ID #13: "Design" of the RFR involves three parameters: (1) choice of material; (2) thickness of the foil; and (3) the pattern etched in the foil. These parameters will be selected according to the criteria discussed below.

Phase I has demonstrated that a promising pattern can be etched in either beryllium copper or stainless steel foil in 0.05 mm thickness. One those two materials will be chosen. Each of those materials has both advantages and disadvantages relative to the other. The choice will depend upon concurrent decisions regarding pattern and thickness. It will also depend upon a prediction of the probable direction of pattern and thickness changes in RFRs #s 2 and 3. It would not be desirable to change materials as well as thicknesses and patterns during the course of the development because that would introduce too many variables to allow meaningful evaluation of results with just three test iterations.

The thickness of the foil determines the hydraulic radius of the flow passages and thus affects Reynolds number in the regenerator. Foil thickness also affects specific area. Computer analysis permits optimization of the Reynolds number for a given configuration of cryocooler in terms of the computer model. However, computer models are not necessarily definitive when the configuration is new and untested, as is the case with the RFR. Foil thickness is among the most important of the parameters that can be varied in the course of the test program.

A pattern must be etched into the foil in order to establish the flow passages. The basic pattern that was demonstrated in Phase I appears to be the best choice. However, variation in the width

of pattern components will alter the fill factor of the regenerator as well as flow patterns. Thus, this parameter is variable in the most complex manner of the three variable parameters. To make the most of the three-iteration test plan, the initial pattern will be chosen to contrast with other patterns to be tested in subsequent iterations.

ID #14: "Fabrication" covers four operations: (1) preparation of artwork for the pattern to be etched on the foil; (2) actual preparation of the foil; (3) rolling the foil to create the regenerator; and (4) installation of the RFR in the displacer. These subtasks are described separately in ID #s 15, 16, 17 and 18.

ID #15: "Artwork" covers preparation of a negative that carries the pattern. This negative is generated by plotting a computer-generated pattern on transparent Mylar using a Gerber plotter. This is an extremely precise process, as the pattern is in micron dimensions. Separate artwork must be generated for both sides of the foil, and must be kept in proper register. Quality control is particularly critical in this step.

ID #16: "Foil" covers preparation of the etched foil. First, plain foil is coated with a photoresist. Next, the artwork is placed on the foil and the foil is exposed to light, creating a contact print on the foil surface. The foil is then washed to remove a portion of the photoresist. (Two types of photoresist are available; with one, the unexposed portion is washed away, with the other, the exposed portion). The foil is then place in the etching bath and the portions from which the photoresist has been removed are etched away, creating the pattern in the foil.

ID #17: "Rolling" covers the process of rolling the etched foil into a cylinder for insertion into the regenerator cavity. This is a delicate operation and some experimentation will be required to develop techniques that will insure a tight, uniform roll with no unintended flow passages and no disruption of the pattern. One possible problem is the center of the roll. Although techniques have been developed in the rolled spring industry to create rolls of metal with essentially zero radius in the center, it is not clear that those techniques will work with the etched foil of an RFR. Experimental work will be conducted initially with plain foil and later with reject samples of etched foil before rolling of the final RFR is attempted.

ID # 18: "Assembly" is the installation of the first RFR in the displacer of the test-bed cryocooler. Because the objective is to install the RFR with essentially zero radial clearance, techniques must be developed to compress the roll slightly and to insert it without damaging the edges of the foil and thereby altering the flow path dimensions at the critical point of entry of fluid into the regenerator. Because the pattern will allow for a certain amount of compression of the foil, it should be possible to squeeze the roll slightly for insertion without permanently deforming it.

ID #19: "Evaluation" covers the first round of performance tests of the completed RFR. Testing will be accomplished both at the contractor's facilities and at the regenerator test facility of the NIST, under a subcontract. The in-house test program is described under tasks ID #s 20 and 21. The NIST testing program is described in task ID #22. These tests will provide insight into the accuracy of the computer predictions previously made in Phase I and II.

ID #20: "Flow inspection" will determine whether the test regenerators destined for in-house testing and for testing at NIST are similar in pressure-drop characteristics in continuous-flow tests. It will also provide a basis for comparison between the RFR and the benchmark stacked-screen regenerators.

ID #21: "In house" evaluation means a program of testing over a range of operating conditions of the test-bed cryocooler at the contractor's facility. It will include analysis of pressure drop over the operating cycle of the test-bed cryocooler. This will be the first performance test of the new RFR concept in an actual cryocooler. It will permit comparison with data obtained in task ID #4 for the test-bed cryocooler equipped with the original stacked screen regenerator.

ID #22: "At NIST" means evaluation of the RFR in the NIST regenerator test facility in Boulder, Colorado. The NIST test program will provide information on the pressure drop and heat transfer characteristics of the RFR in a highly controlled setting. This testing procedure will provide a cross-check on results obtained in in-house experiments.

ID #23: "Mid report 1" will summarize the results of the work done through the first round of testing. It will be the working document for the critical design review (CDR) referred to in task ID #24.

ID #24: "CDR": The first CDR will address the results of the first round of testing and draw the conclusions that will become the basis for the decisions to be made before the next round of testing. This meeting will include representatives of the contractor and the procuring facility.

ID #s 25 - 36: The second and third iterations of the RFR will be designed, fabricated and tested in a manner similar to the procedure used with the first. However, with the experience gained as the project progresses, the time required for each successive iteration will decrease.

ID #37: "RFR#4 for SSC #2" includes the design and fabrication of an RFR for the SSC #2, the Air Force 65 K Standard Spacecraft Cooler designed and built by Hughes Aircraft. These steps are covered separately in tasks ID #s 38-40.

ID #38: "Design" of RFR#4 will draw on experience from the earlier series of tests and from computer analysis, interpreted in light of the earlier predictions and results. It will be designed to fit a regenerator cavity with dimensions that are different from the dimensions of the testbed cryocooler. Otherwise, it will be similar to RFR#3.

ID #39: "Fabrication" includes all of the elements of fabrication of the first 3 RFR samples, including artwork, foil etching, rolling and assembly. The foil will be longer than that used in earlier RFRs, which may require modifications in tooling.

ID #40: "Evaluation": Because RFR#4 will be different from the first three RFR samples, it will not be possible to test it in house; testing will take place only at NIST.

ID #41: "Delivery of 2 RFRs": Two RFRs designed to fit and function in the SSC #2 will be delivered to Hughes Aircraft for testing. Testing in that machine is outside of the scope of work proposed for this contract. The RFRs delivered for the SSC will also fit and function in the "Brilliant Eyes" cryocooler.

ID #42: "Final report": Preparation of the final report, summarizing the work done from the beginning of the project to completion of the experimental work, will be the final task of the project.

SECTION 4.0

POSTAPPLICATIONS

4.1 RELATIONSHIP WITH FUTURE RESEARCH OR R AND D

The completion of this Phase II effort will result in improved regenerator technology for spacecraft cryocoolers - specifically the RFR to be installed in the Air Force 65 K SSC. Phase III will include both further development for other Government applications such as "Brilliant Eyes" and introduction of the technology to commercial applications.

Insofar as Phase III is a continuation of a Government-funded project to develop hardware for Government needs, the following opportunities appear:

- Optimization of spacecraft cooler design to take full advantage of the superior characteristics of the RFR concept.

- Introduction of RFR regenerators into tactical coolers.

- Optimization of tactical cooler design to take full advantage of the characteristics of the RFR.

The commercial portion of the Phase III program will introduce the RFR into commercial cryocoolers used in cryopumping systems used for computer chip manufacture and magnetic resonance imaging systems use in medical diagnosis.

While Phase II will prove the concept, Phase III will develop commercially viable products. Commercial development will require further refinement of the variable parameters of the RFR. They include the more general design considerations of regenerator length and diameter as well as the selection of foil material and determination of optimum foil thickness and micro-machined pattern for each potential application. The relationships between these variables are complex. A complete exploration of possible combinations and permutations is beyond the scope of Phase II. It appears likely that incremental improvements in performance of RFR-equipped cryocoolers may continue for a long time.

4.2 POTENTIAL POSTAPPLICATIONS

Immediate applications of the new RFR technology are in cryocoolers cooling infrared sensors and other electronic devices. However, the technology has much broader application in regenerative gas cycle machinery of all types, including both defense and civilian applications. Defense applications include tactical cryocoolers for night vision systems, gunsights and missile guidance systems. Civilian applications include cryopumps used in computer chip manufacture and coolers for radiation shields in MRI systems used in medical diagnosis. Widespread use of superconducting devices will create additional applications.

One intriguing possibility is that RFRs can be fabricated from materials with high specific heat at very low temperatures. Candidate materials include neodymium and the harder alloys of lead. Regenerators of these materials could replace the lead shot regenerators in the second stages of Gifford-McMahon cryocoolers. As Ref. 1 noted, beds of packed spheres have the lowest ratio of heat transfer to friction factor of any standard regenerator geometry at low Reynolds numbers. Thus, major improvements in performance of these machines may be possible. The benefits may be especially important in the cryopumping and MRI cooling applications that use Gifford-McMahon coolers.

SECTION 5.0

CONCLUSIONS

The proposed RFR combines the best features of wire mesh screens and parallel flat plates. Flat plates are theoretically superior because they offer the highest ratio of heat transfer to pressure drop loss. However, solid flat plate regenerators are unstable: they do not allow cross flow between layers, and without cross flow, uneven flow patterns develop and persist. Moreover, solid flat plates conduct heat well in the direction of fluid flow, tending to destroy their regenerative effectiveness.

Screen regenerators are stable, with cross flows quickly equilibrating any imbalance in temperature at any cross section Heat conduction losses are low. However, flow paths through a screen regenerator are highly irregular, both in direction and in hydraulic diameter. Flow velocity varies greatly from point to point. Wires in screens create 'wind shadows' for downstream wires. As a result, stacked screens are markedly worse than flat plates in terms of their ratio of heat transfer to pressure drop losses.

Stacked screens cannot be analyzed by solving the Navier-Stokes equations. However, those equations can be, and were, solved for the RFR. The results confirmed the superiority of the flow characteristics of the RFR and generated the data necessary to model RFR-equipped cryocoolers with Stirling cycle codes.

The superiority of the proposed RFR over screens was quantified for the SSC #2 built for the Air Force by Hughes Aircraft. That cryocooler was modelled using two different Stirling cycle codes. Each code was validated by comparing its predictions with measured performance of the SSC #2. Each code predicted at least 50 percent more refrigeration at 45 K for an SSC #2 equipped with RFR than for the same machine with its original stacked screen regenerator. Further improvements could be expected if the dimensions of the regenerator cavity were optimized for the RFR

There is no serious doubt that the RFR can be made. The proposed RFR will be fabricated of thin foil that has been sculpted in a precise, microscopic pattern, combining the superior flow characteristics of parallel plates with the flow stability of stacked screens. Samples of the pattern were successfully created in beryllium copper. Although the pattern is too small to be seen clearly with the naked eye, it is remarkably consistent and exact when seen under the microscope.

This project was successful in all respects. Theory was confirmed with calculations, design techniques were developed, and the key fabrication technique was demonstrated.

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APPENDIX

THE COMPUTER MODELS

Net performance for the Hughes Aircraft SSC #2 was calculated for both the original-equipment wire mesh regenerator and for the new RFR. Comparison of the results shows that the RFR improves performance of that cryocooler by more than 20 percent at 60 K, and by 100 percent at 40 K. These calculations made use of three separate computer models, of which one was a computational fluid dynamics (CFD) code and the other two were Stirling cycle models.

The Stirling cycle models calculated performance with both the original regenerator and the RFR. The only difference in the calculations was in the heat transfer and pressure drop coefficients for the regenerator. For wire mesh, these coefficients are necessarily based upon empirical data because it is not yet possible to solve the complete set of Navier-Stokes equations for a random medium such as stacked screens of wire mesh.

There are not yet any empirical friction and heat transfer coefficients for the RFR because the idea is new and as yet untested. Thus it became necessary to develop those coefficients independently. However, it is possible to solve the Navier-Stokes equations for a uniform, repeating pattern such as that presented by the pattern etched into the RFR. The heat transfer and pressure drop coefficients for the RFR were therefore based upon values calculated using the CFD code. Those predictions for friction and heat transfer coefficients can be accepted with some confidence, as they could be, and were, generated from first principles. Moreover, the accuracy of the CFD code was verified by testing it with a problem with a known solution.

The codes, and the techniques employed in their use on this project are discussed in greater detail below.

microCOMPACT is a computer software package developed originally for use on mainframes under the direction of Suhas V. Patankar, Professor of Mechanical engineering at the University of Minnesota. The PC version of microCOMPACT is offered commercially by Innovative Research, Inc., of Minneapolis. Descriptive literature about the code is attached.

To determine heat transfer and pressure drop coefficients, the RFR pattern was modelled in two dimensions on microCOMPACT for a range of Reynolds numbers typical for cryocooler regenerators. The equations that describe the resulting curve were then derived. These equations were then imported into the Stirling cycle codes used to model overall performance of a cryocooler.

The Stirling Simulations

Two computer models were used to analyze the version of the Air Force 65 K SSC developed by Hughes Aircraft Company (the "SSC #2"). One model is the Urieli/Yaron code, which was

developed specifically to model cryocoolers. The other is the MS*2 Stirling Cycle Code, which is a general-purpose model of all types of Stirling cycle machines, including cryocoolers.

The Urieli/Yaron Code

The Urieli/Yaron cryocooler analysis program is "second order". The code assumes that the compression space is adiabatic and that all of the other spaces are isothermal. It uses friction and heat transfer coefficients based upon extensive experimental work conducted by Yaron with 400, 500 and 635 mesh screen regenerators. The coefficients were obtained from direct measurements of regenerator performance (pressure drop and temperatures) in an instrumented cryocooler equipped with a differential pressure transducer. The code has been used extensively in the design and evaluation of common module split and integral Stirling cryocoolers.

To validate the Urieli/Yaron code for use in this project, it was used to model the SSC #2, for which Hughes Aircraft furnished detailed data on geometry, dimensions and operating conditions. The results were compared to measured performance results supplied by Hughes. The two performance curves are shown in Figure A-1.

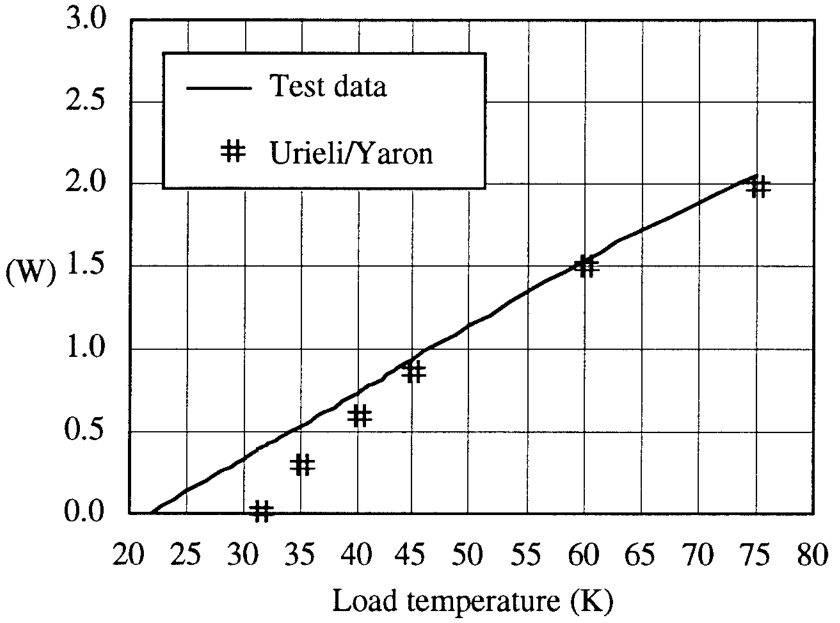

Figure A-1. Urieli/Yaron modelled performance and Hughes test data of the SSC #2.

The Urieli/Yaron model was then modified to incorporate the heat transfer and pressure drop coefficients developed by the CFD code for the RFR regenerator. The results of those changes were a substantial improvement in performance at all temperatures modelled, as reported above.

The MS*2 Stirling Cycle Code

The MS*2 Stirling Cycle Code is a "third order" code that continuously models both adiabatic temperature changes and heat transfers in all spaces of the cryocooler, including expansion and compression spaces, heat exchangers, regenerators and connecting ducts. It deals with the regenerator losses continuously throughout the computational cycle. Results can be adjusted at the end of a run for shuttle losses and other conduction losses in cylinder, displacer and insulator. Those losses must be calculated separately, by hand, based upon the materials and dimensions of a particular machine [Ref. 7].

To obtain satisfactory numerical accuracy while modelling cryocoolers, the MS*2 code must be run for several hundred cycles to fully develop thermal balance in the regenerator. Moreover, to obtain a numerically accurate answer, the effect of "convergence" must be taken into account. [Ref. 6]. That is, the numerical accuracy of the code improves as the number of time steps and space steps increases and the size of each step correspondingly decreases. The improvement is close to linear, so it is possible to project the exact solution closely by modelling the same geometry and operating conditions with varying numbers of time steps and space steps and projecting the result for infinite time steps and space steps. In this case, convergence was obtained based upon a projection from two data points for each temperature considered. High resolution was obtained with 200 space steps and 2880 time steps per cycle, low resolution with 101 space steps and 1440 time steps.

Because the displacer of the SSC #2 has a drive rod on the warm end, the volume in the space behind the displacer decreases as the volume in the expansion space increases. The MS*2 code does not directly model three variable volumes. To model accurately the mass flow through the cooler tube at the displacer end, the expansion space volume was reduced. Because the mass flow per unit of volume is much larger in the expansion space than in the space behind the displacer, the volume adjustment was relatively slight even at the upper end of the temperature range modelled.

The refrigeration obtained with that modelling assumption was adjusted proportionally to the initial volume adjustment to obtain refrigeration in 100 percent of the actual displacement in the expansion space at each operating temperature. The results predicted for the Hughes Aircraft SSC #2 equipped with its original wire mesh regenerator were slightly higher than those measured by Hughes. The comparison between Hughes' measured results and the MS*2 code are shown in Figure A-2.

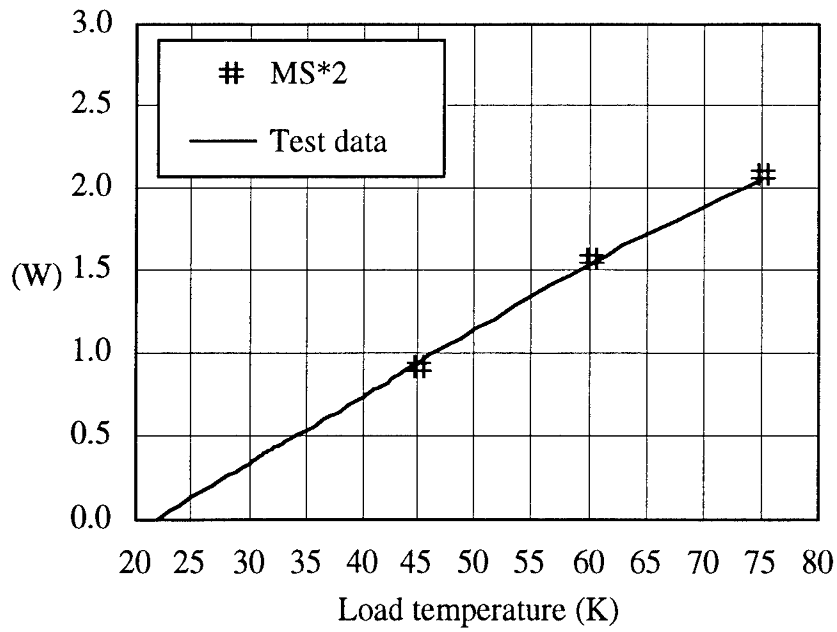

Figure A-2. MS*2 modelled performance and Hughes test data of the SSC #2.

The MS*2 code was modified to incorporate the heat transfer and pressure drop equations for the RFR as determined by the CFD code. With these modifications, the MS*2 code also predicted substantial improvements in performance of the SSC #2 at all operating conditions modelled. The results are reported above.

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